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13. ABSTRACT (Maximum 200 words)  Significant progress was made to further advance the quantum well infrared photodetector (QWIP) technology in two areas: 1) designing, demonstrating, and understanding voltage tunable two-color QWIPs, and 2) understanding the light coupling mechanism in the so-called quantum grid infrared photo-detectors.  We have also been working on imprint technology to create pillars which can be used to enhance the performance of the photo detectors. The NIL molds with different period and different shape of the pillars have been created. Implementation of the small pillars to photodetectors are in progress.				
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Enclosure 1

## **Attachment I**

To further develop the GaAs/Al<sub>x</sub>Ga<sub>1-x</sub>As QWIP to fully realize its potential for high resolution long wavelength large array imaging applications, it is deemed important to improve the detectivity of the device to broaden the range and selectivity of its spectral characteristics, and to have a technology for mass production. Towards this goal, our research focused on three areas:

(i) voltage tunable QWIPs for multi-color detection, (ii) quantum grid device structure to further enhance detectivity, and (iii) investigation of nanoimprint technology for large volume production.

## Attachment II

### 5. Summary of Most Important Results

In this final technical report we briefly describe our accomplishments in further developing the GaAs/Al<sub>x</sub>Ga<sub>1-x</sub>As quantum well infrared photo detector (QWIP) for high resolution long wavelength large array imaging applications. Research in three areas are discussed:

#### a. Voltage tunable QWIPs

In existing literature, two-color QWIPs based on electron transfer between coupled QWs suffered from the presence of the shorter wavelength peak at all bias voltages  $V_b$ . We investigated this problem in **R3** and more in detail in **R6** by studying the bias dependence of absorption coefficient and photoconductive gain  $g$  as a function of wavelength at 10 K. We fabricated such a detector with a peak wavelength of  $8\text{ }\mu\text{m}$  for both bias polarities but a voltage tunable cut-off wavelength ( $9\text{ }\mu\text{m}$  for  $V_b > 0\text{ V}$  and  $11\text{ }\mu\text{m}$  for  $V_b < 0\text{ V}$ ). We used corrugated-QWIPs with different corrugation periods to extract  $\alpha$  and  $g$  for different values of  $V_b$ . We found  $\alpha \approx 0.1\text{ }\mu\text{m}^{-1}$  in the  $6\text{--}12\text{ }\mu\text{m}$  range with small peaks at  $8$  and  $9.8\text{ }\mu\text{m}$  for  $V_b > 0\text{ V}$  and at  $10\text{ }\mu\text{m}$  for  $V_b < 0\text{ V}$ .  $g$  had a pronounced peak at  $7.8\text{ }\mu\text{m}$  for both bias polarities and determines the lineshape of the QWIP spectral responsivity. These results were attributed to insufficient electron transfer between the coupled QWs and to low tunneling probability of the longer wavelength photoelectrons.

Having identified the fundamental problems in achieving tunable peaks, we then redesigned the coupled wells with thicker center barrier layers and graded cladding barriers. Consequently, a two-color quantum-well infrared photodetector with voltage tunable detection peaks was demonstrated in **R5**. It is based on electron transfer between two asymmetric coupled quantum wells under an applied bias. At 10 K, the peak detection wavelength is  $7.5\text{ }\mu\text{m}$  for positive bias when the electrons reside in one of the wells, and switches to  $8.8\text{ }\mu\text{m}$  at a large negative bias when the electrons are transferred to the other well. The electron activation behavior of dark current in this detector depends on both temperature and bias. We observed two distinctive activation energies under negative bias for two different temperature regimes, and one under positive bias. The voltage tunability of the detector and the activation energy are well explained by the calculated energy levels and oscillator strengths of intersubband transitions in the structure. This voltage tunable two-color QWIP, when integrated with time-multiplexed readout circuits, will greatly simplify the two-color FPA production and improve its yield.

#### b. Quantum grid infrared photodetectors

In **R4**, rigorous electromagnetic modeling based on a modal solution of the pertinent boundary-value problem was performed to study the coupling mechanism of light in quantum grid infrared photodetectors (QGIPs) with lamellar patterns. The theory shows that the vertical field component and the absorption quantum efficiency  $\eta$  can be strongly enhanced by judiciously adjusting the width  $w$  of individual grid lines. This enhancement is further increased if the tops of the grid lines are covered by metal strips which behave as a collection of dipole scatterers. We have experimentally verified the dipole scattering characteristics with different  $w$ , and found that the variation of  $\eta$  agrees very well with the theory. We also found that, as expected, the conductivity

of the metal strips affects  $\eta$  significantly due to internal dissipation. With this physical understanding, design of a narrow band couplingscheme to achieve a quantum grid infrared spectrometer is now feasible.

### c. Nanoimprint lithography

We have fabricated large pillar arrays using nanoimprint lithography. These pillar arrays can be used to enhance the performance of quantum-dots QUIPs.

The self-assembled quantum dots provide a simple realization of three-dimensional confinement in a semiconductor matrix. The formation of quantum dots has been studied in different systems, such as Ge/Si, InAs/GaAs and CdSe/ZnSe. However, the dots are randomly located which limits many potential applications and makes the studies of the properties of each dot difficult. By using a nanostructure-patterned substrate for the formation of the quantum dots, the locations of the dots are no longer random but controlled by the pattern on the substrate. Moreover, at certain conditions, the boundary condition of the patterned substrate may help to assemble single domain quantum dot periodic arrays. All of those will benefit both the physics studies and the applications of quantum dots. Using the pillar mold and NIL, we provide a fast, easy and low-cost method to pattern the substrate, and consequently better controlled growth of quantum dots.

Shown in Fig. 1 is a 190 nm period large area pillar array nanoimprint lithography (NIL) mold. The pillar array is made of SiO<sub>2</sub> on top of a Si wafer and covers whole 4-inch wafer area. The pillar array mold was made using interference lithography and a double-layer NIL process. In the beginning, a 190 nm period SiO<sub>2</sub> grating on top of a Si wafer was fabricated using interference lithography and RIE etching. The grating was used as the NIL mold for the double NIL process to make the pillar array mold. In the double NIL process we started with a Si wafer with 200 nm thick thermally grown SiO<sub>2</sub>, the first NIL and etching defined 190 nm period gratings in SiO<sub>2</sub> layer. Next, we spun NIL resist on top of the grating, and performed NIL again with the grating on the mold oriented orthogonally to the grating on the substrate. After SiO<sub>2</sub> etching, pillar array formed in the SiO<sub>2</sub> layer. After obtaining the pillar mold, single NIL process can duplicate the pillar array mold into pillar array daughter molds. They were used to fabricate large area arrays of pillars or via holes. (Fig. 2)

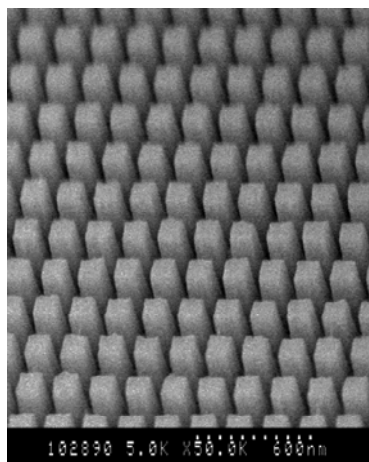


Figure 1

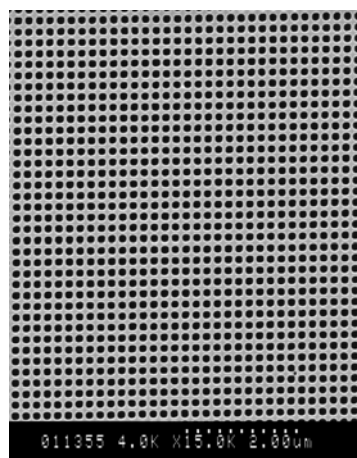


Figure 2

## Attachment III

### 1. List of publications

#### Refereed publications

- R1. "Optimization of high detectivity infrared hot-Electron transistors at low temperature", Trans. Elect. Devices, 48, 1318 (July 2001), J. Yao, K. K. Choi, and D. C. Tsui.
- R2. "Characteristics of QWIPs at low background", Infrared Physics and Technology, 42, 221 (June 2001), K. K. Choi, S. W. Kennerly, J. Yao and D. C. Tsui.
- R3. "Towards a voltage tunable two-color quantum-well infrared photodetector" Applied Physics Letters, 80, 538, (Jan 2002), A. Majumder, K. K. Choi, L. P. Rokhinson and D. C. Tsui.
- R4. "Light coupling mechanism of quantum grid infrared photodetectors" Applied Physics Letters, 80, 868, (February, 2002) J. Mao, A. Majumder, K. K. Choi, D. C. Tsui, K. M. Leung, C. H. Lin, T. Tamir, and G. A. Vawter.
- R5. "Two-color quantum well infrared photodetector with voltage tunable detection peaks", Applied Physics letters, 80, 707, (February, 2002), A. Majumder, K. K. Choi, J. L. Reno, L. P. Rokhinson and D. C. Tsui.
- R6. "Electron transfer in voltage tunable two-color infrared photodetectors", Journal of Applied Physics, 91, 4623 (April 2002) A. Majumder, K. K. Choi, L. P. Rokhinson, J. L. Reno and D. C. Tsui.

#### Conference presentations

- C1. "Voltage tunable two color quantum well infrared photodetector", A. Majumdar, L. P. Rokhinson, D. C. Tsui, and K. K. Choi, APS March Meeting, Seattle, March 12-16, 2001.
- C2. "Two-color quantum well infrared photodetectors" A. Majumdar, K. K. Choi, L. P. Rokhinson, D. C. Tsui, and J. L. Reno, ITQW'01, Monterey, Sept 9-14, 2001.
- C3. "Light coupling in corrugated and quantum grid IR detectors", K. K. Choi, T. Tamir, J. Mao, and D. C. Tsui, APS March Meeting, Indianapolis IN 18-22 Mar 2002.
- C4. "Two-color quantum well infrared photodetector", A. Majumdar, K. K. Choi, J. L. Reno, L. P. Rokhinson, and D. C. Tsui, APS March Meeting, Indianapolis IN 18-22 Mar 2002.